

Purdue University

Parasitic Loss Control Through Surface Modification



Principle Investigator: Farshid Sadeghi, Ph.D.

Tom J. George, Project Manager, DOE/NETL

Ronald Fiskum, Program Sponsor, DOE/EERE

COOPERATIVE AGREEMENT DE-FC26-02NT41340

Awarded (4/1/2002, 36 Month Duration)

Total Contract Value: \$575,317 - DOE Share: 459,41

Purdue Cost Share: \$115,903



Presentation Outline

- Objective
- Schedule
- Personnel
- Background & Motivation
- Progress to Date
 - Experimental Studies
 - CAD models of test rig PRCLR
 - PRCL Rig
 - Sample results

Presentation Outline

(Continued)

- Analytical Studies
 - Kinematics/Dynamics
 - Secondary Motion
 - Piston/Cylinder Lubrication
 - Piston Ring – Cylinder Liner Lubrication
- Results
- Future Work

Overall Objectives

- The objectives of this study are to analytically and experimentally investigate the effects of surface patterning and features (e.g. dimples, negative skewness, etc.) on the lubrication mechanism of the piston ring and cylinder liner (PRCL) interface.

Objectives

(continued)

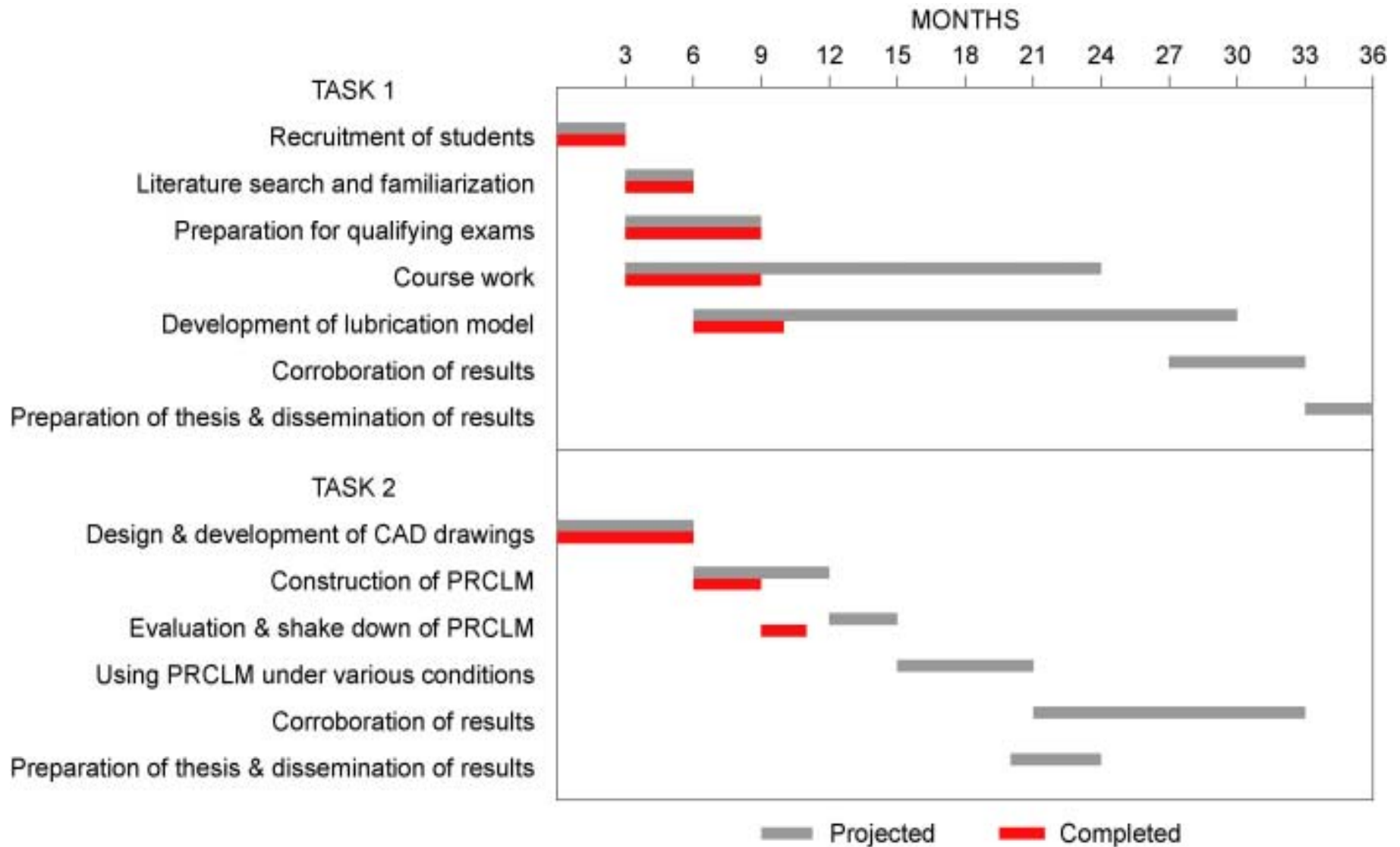
- **Task 1: Analytical study objectives:** Develop CFD models to simulate mixed, boundary and full film lubrication conditions (TBD & BDC) of the piston ring's motion in the cylinder liner. The model will then be extended to investigate surface patterning and feature effects on lubrication condition and friction reduction at the piston ring cylinder liner interface.
- **Corroboration of analytical and experimental results.**

Objectives

(continued)

- **Task 2: Experimental studies objectives:**
 - Design and develop a bench scale test rig operating under ambient condition.
 - Modify a single cylinder bench scale IC test rig capable of operating in the presence of natural gas.
- The test rigs will be used to measure friction between commercially available and surface pattern rings and cylinder liners operating under various conditions.

Project Schedule



Personnel

- Recruited two Research Assistants

- Nathan Bolander, Ph.D Graduate Student
 - ✓ Analytical Work



- Brian Steenwyk, MS graduate Student
 - ✓ Experimental Work



Motivation

- 20 to 40 percent of engine frictional losses are attributable to the piston-ring assembly (Jeng, 1992)
- The largest frictional force is found in the operating region surrounding TDC, the mixed lubrication regime (Akalin & Newaz, 2001)
- Previous computational models have shown significant gains in tribological performance when micro-dimples are introduced (Zhao & Sadeghi, 2001).

Background & Motivation

Surface Roughness Parameters (Definitions)

- Arithmetic Mean (R_a)

$$R_a = \frac{1}{l_m} \int_0^{l_m} |y| dx$$

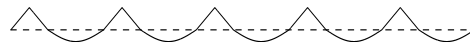
- Root Mean Square (RMS)

$$R_q = \sqrt{\frac{1}{l_m} \int_0^{l_m} y^2 dx}$$

- Skewness (S_k)

$$S_k = \frac{1}{R_q^3} \frac{1}{l_m} \int_0^{l_m} y^3 dx$$

- Surface 1



$R_a(\text{mm})$ $R_q(\text{mm})$ $S_k(\text{mm})$

0.09 0.1151 0.8285

- Surface 2

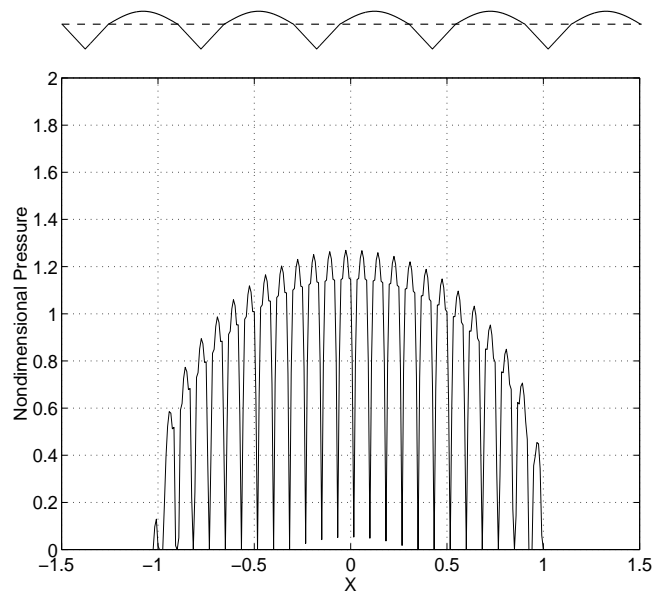


0.09 0.1151 -0.8285

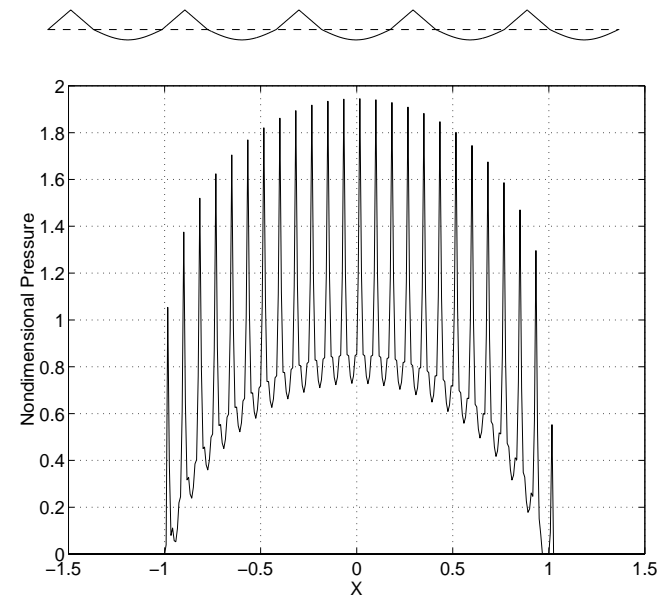
Background & Motivation

(Surface Roughness Effects on Pressure)

- Xu and Sadeghi 1996 and Zhao et. al. 2000 have demonstrated that surfaces with identical $R_a = 0.09\mu\text{m}$ & $RMS = 0.1151\mu\text{m}$ and different skewness can markedly affect the pressure distribution and consequently friction between bodies in contact.



a) Skewness = $-0.8285\mu\text{m}$



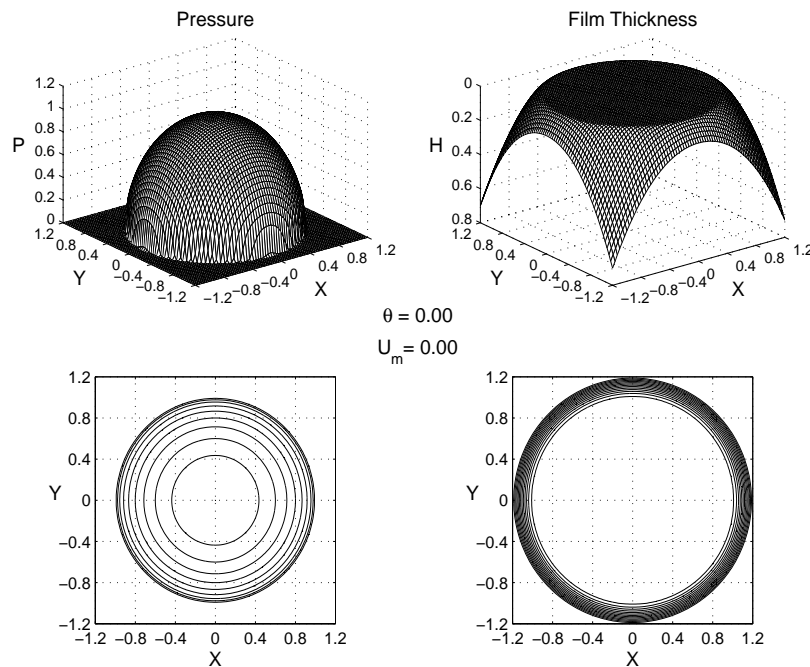
b) Skewness = $0.8285\mu\text{m}$

Pressure distribution between rough surfaces.

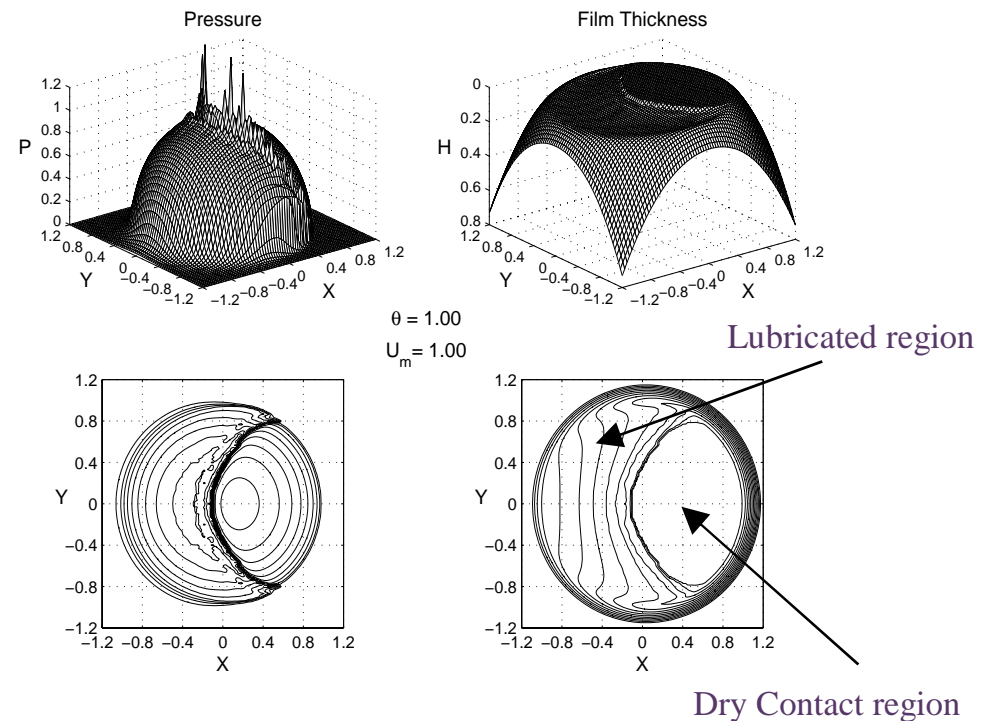
Background & Motivation

(Smooth Mixed Lubrication Model)

- Mixed Lubrication Model for Heavily Loaded Point Contact:
Zhao & Sadeghi [2001](#)



Time $\theta = 0$ ($t = 0$)



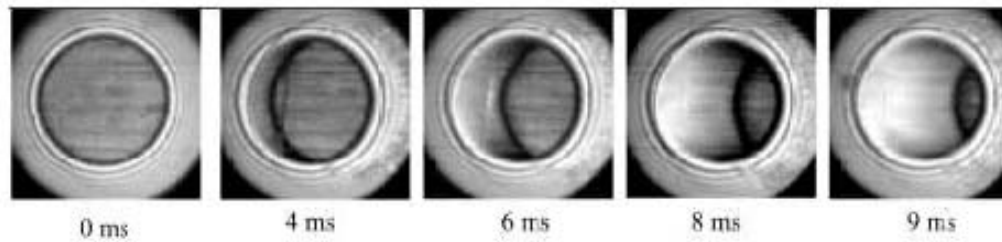
Time $\theta = 1$ ($t = 51.9 \mu s$)

Background & Motivation

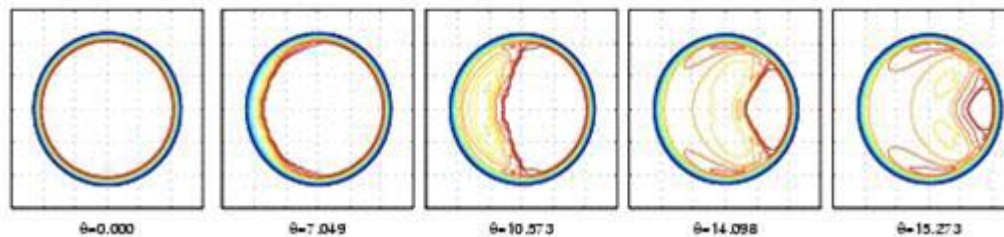
(Corroboration of Experimental & Analytical Results)

- **Mixed Lubrication Model for Point Contact:** Corroboration of analytical (Zhao & Sadeghi 2001) & experimental results (Glovnea & Spikes 2002)

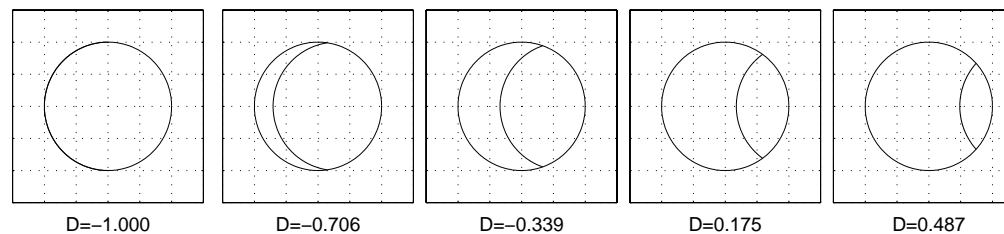
Experimental



Numerical



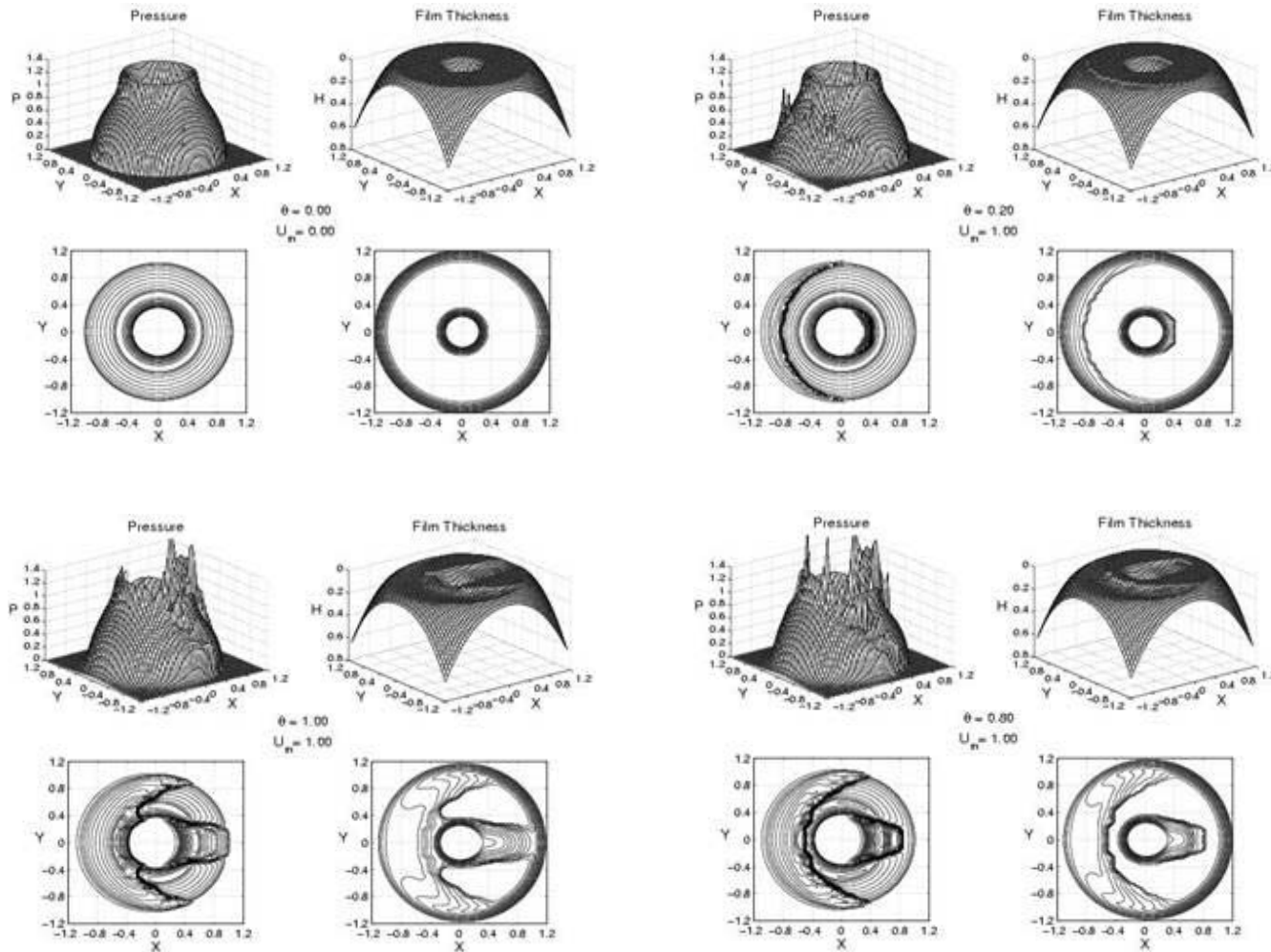
Analytical



Background & Motivation

(Surface Feature (pocket) Effects point Contact)

- Note Lubricant release from the pocket before complete surface separation.



Experimental Investigation

Experimental Study Accomplishments

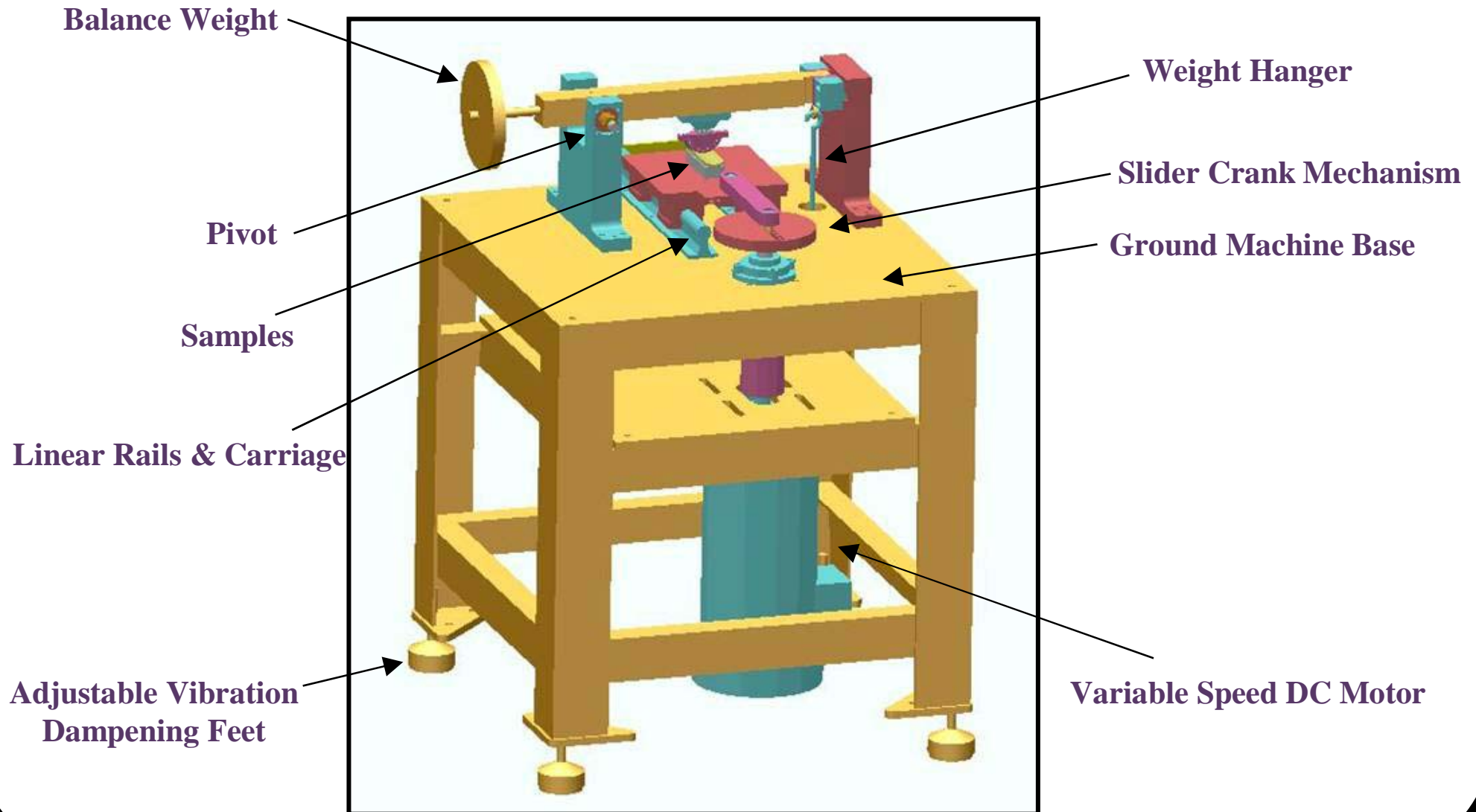
- Designed & developed a bench scale test rig operating in ambient conditions to measure friction at the contact of the PRCL interface

Piston Ring Reciprocating Cylinder Liner Test Rig

(Goals, variables & Attributes)

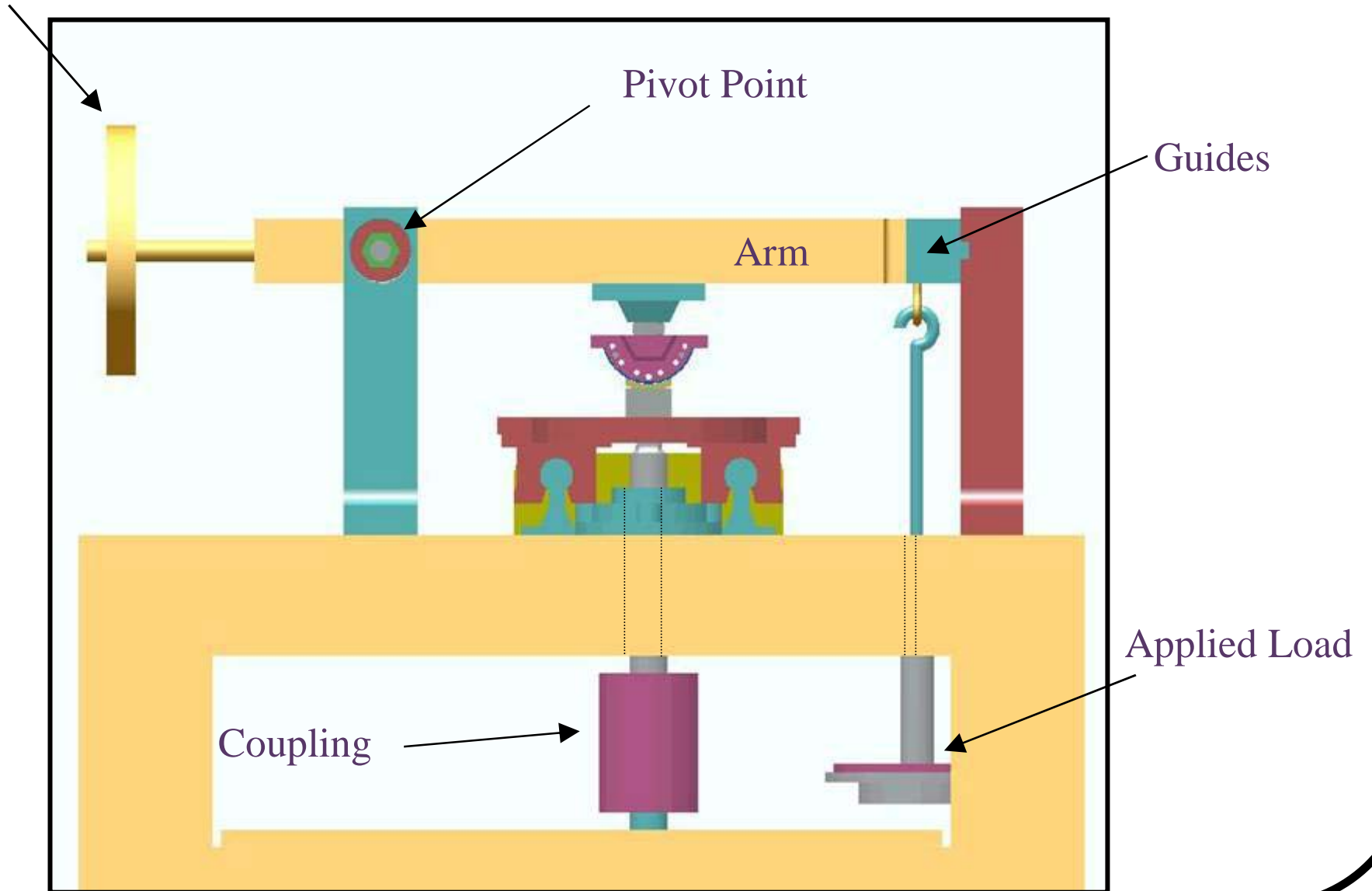
- Controllable conditions:
 - ❖ load, speed, temperature & lubricant condition
 - ✓ Accommodate range of sample sizes:
 - 2" to 5-1/2" bore
 - 9" x 9" carriage size
 - Variable stroke: 1-1/2" to 6"
 - Variable speed direct DC drive
- Will not simulate all the details of an IC engine
- Can measure friction between piston ring, commercially available liners and surface modified liners using a piezoelectric 3-axis force sensor

Piston Ring Reciprocating Cylinder Liner Test Rig

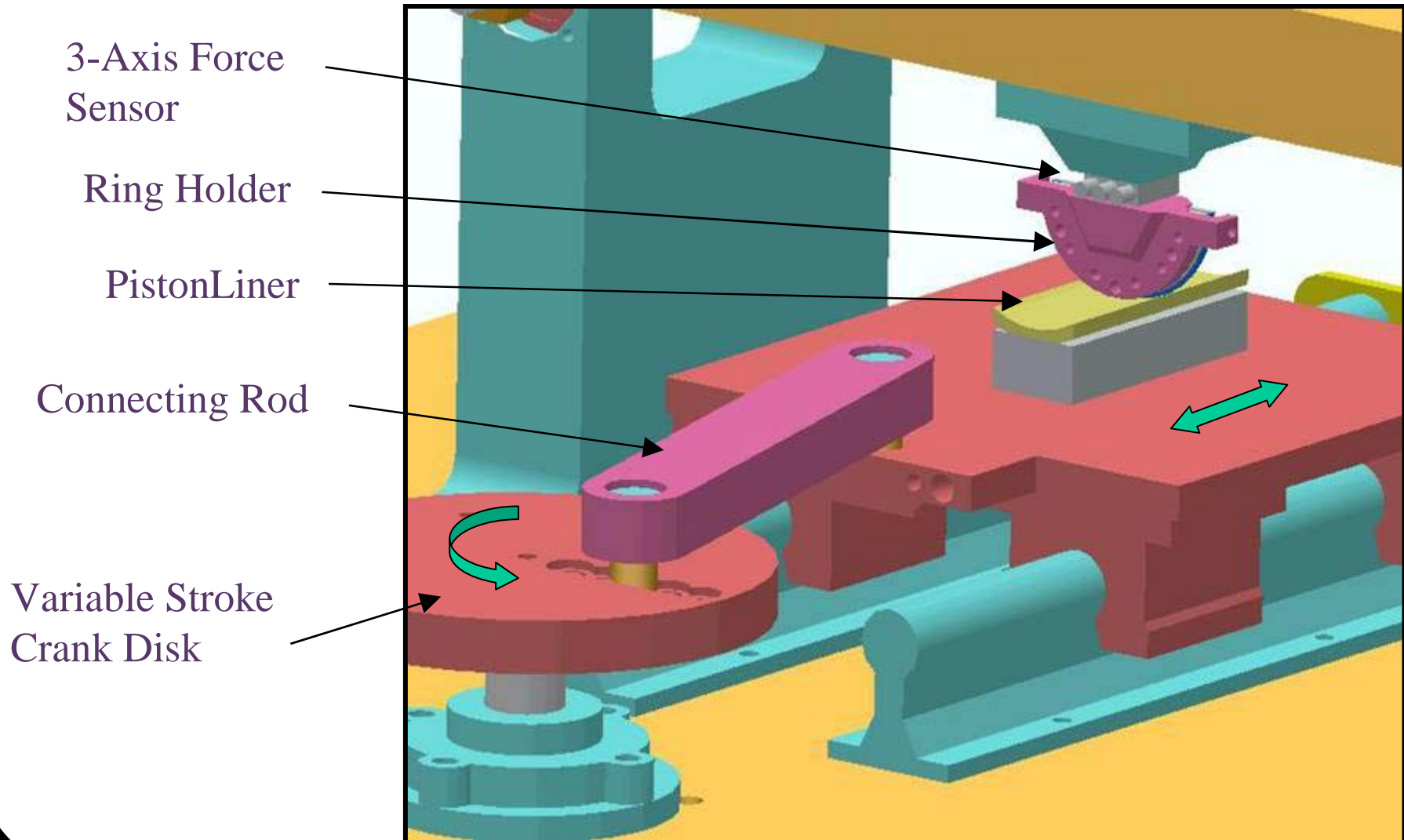


Pivot Arm

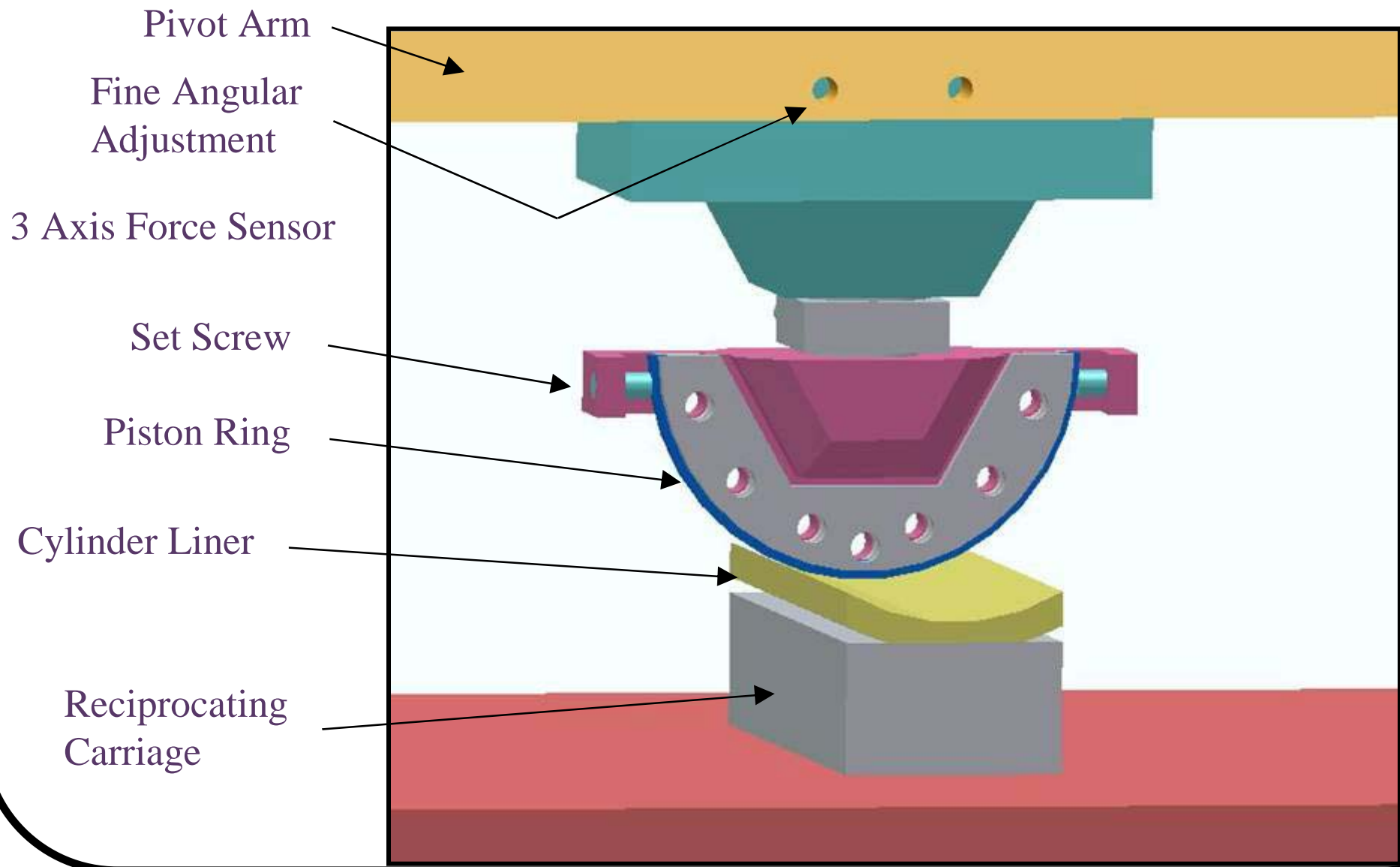
Balance Weight



Friction Measurement



Ring Holder Subassembly



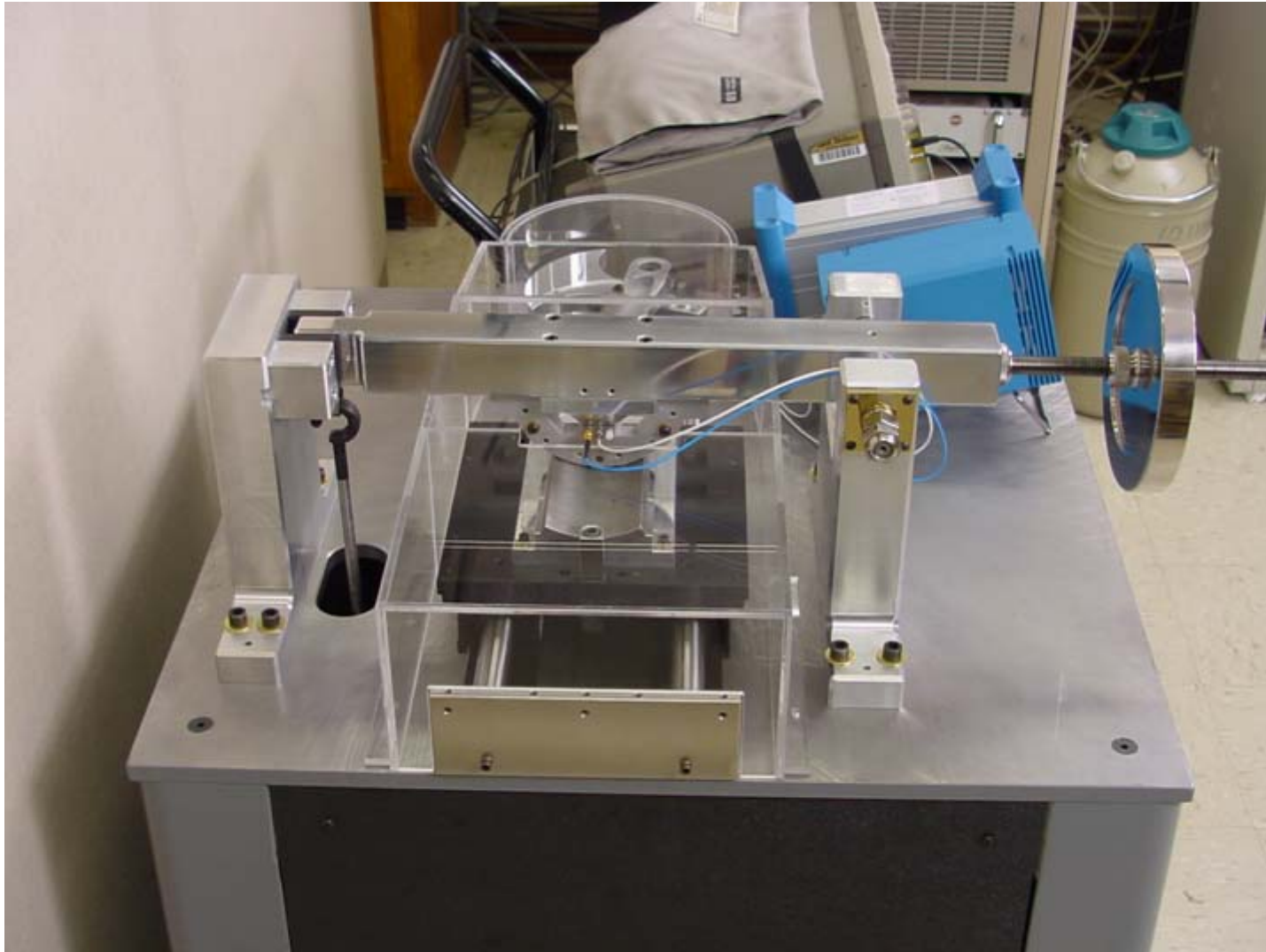
Experimental Study

(Piston Ring Reciprocating Cylinder Liner Test Rig - PRCLR)



Experimental Study

(Piston Ring Reciprocating Cylinder Liner Test Rig - PRCLR)



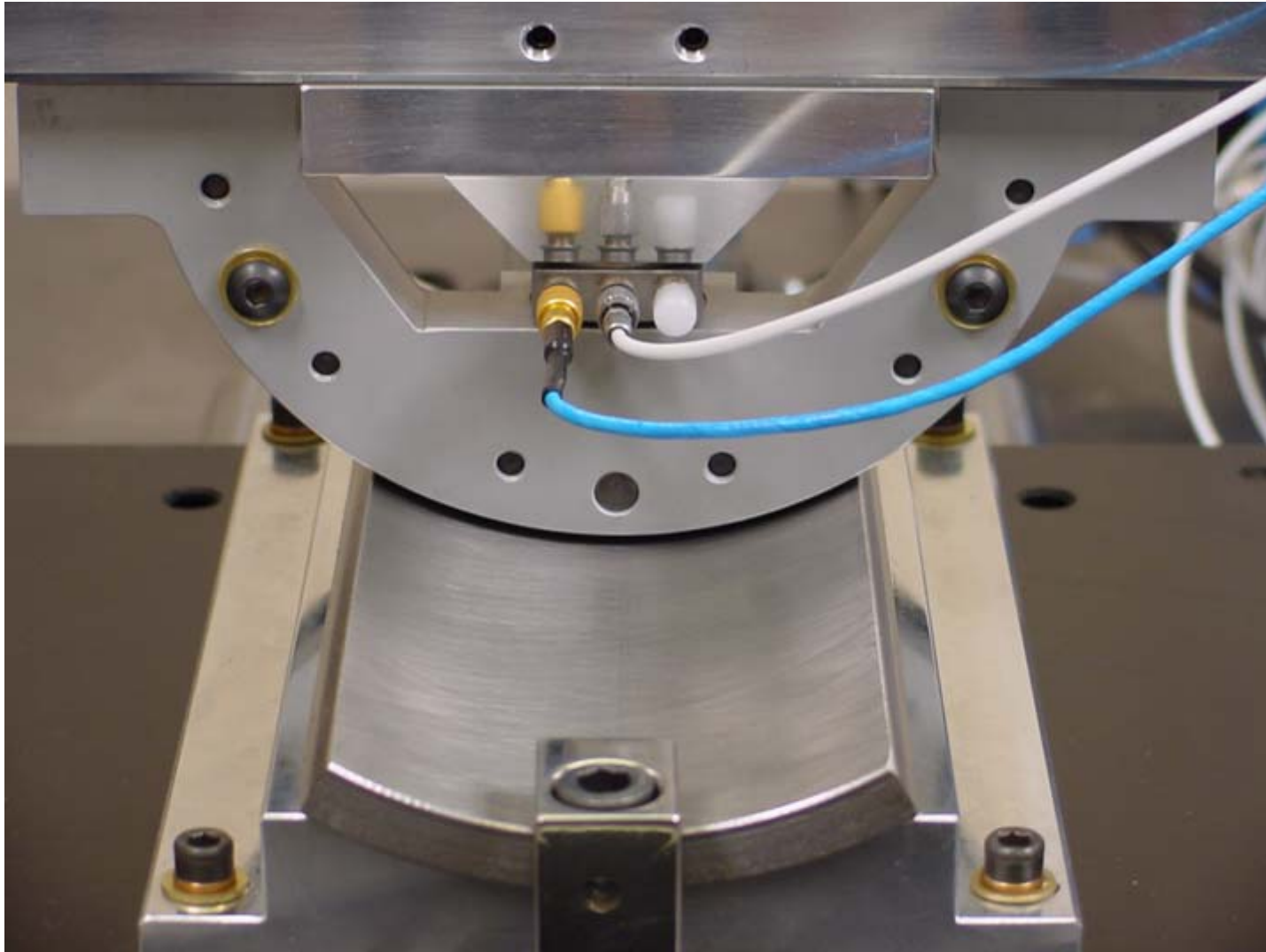
Experimental Study

(Piston Ring Reciprocating Cylinder Liner Test Rig - PRCLR)



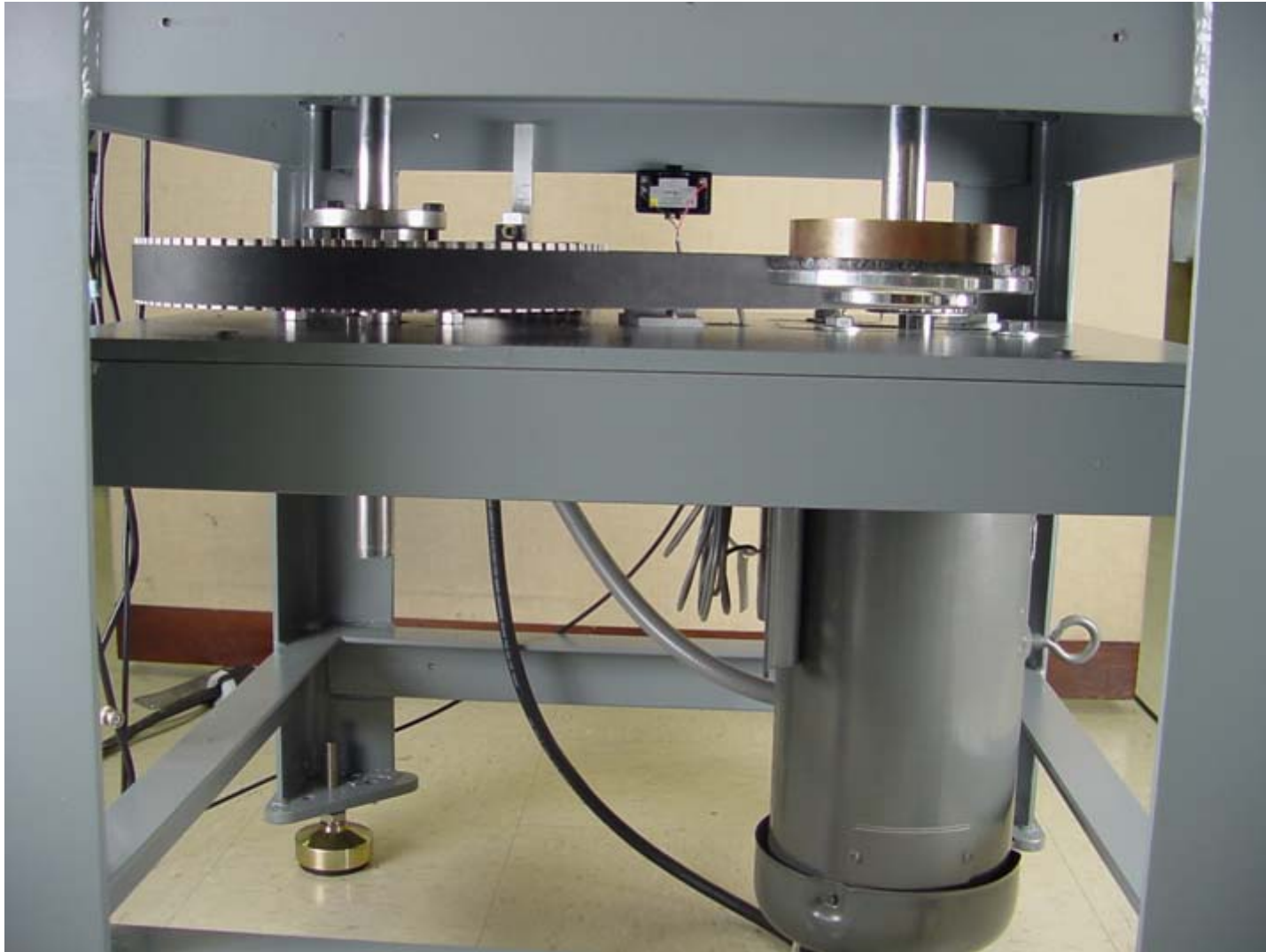
Experimental Study

(Piston Ring Reciprocating Cylinder Liner Test Rig - PRCLR)



Experimental Study

(Piston Ring Reciprocating Cylinder Liner Test Rig - PRCLR)



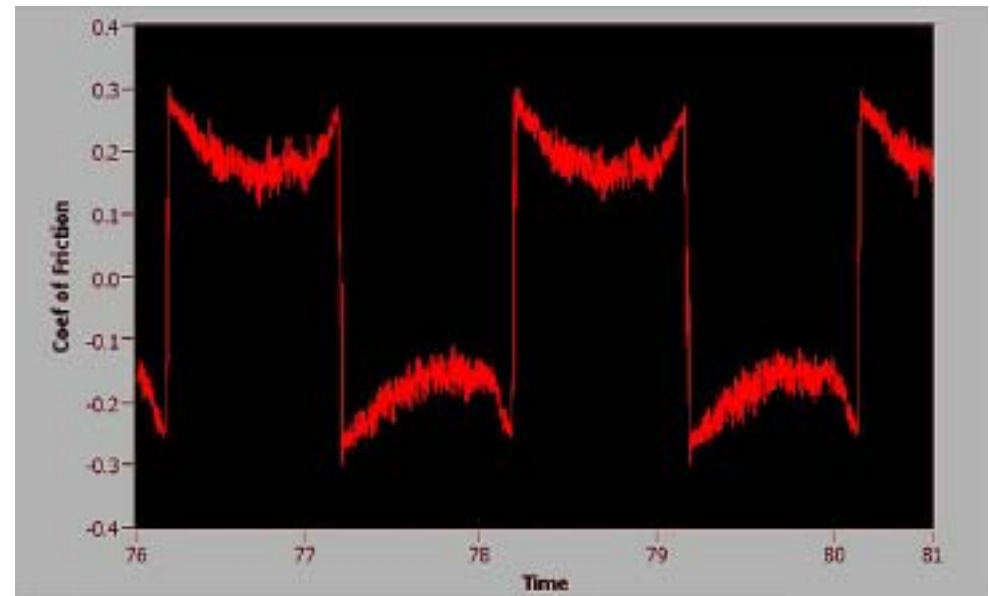
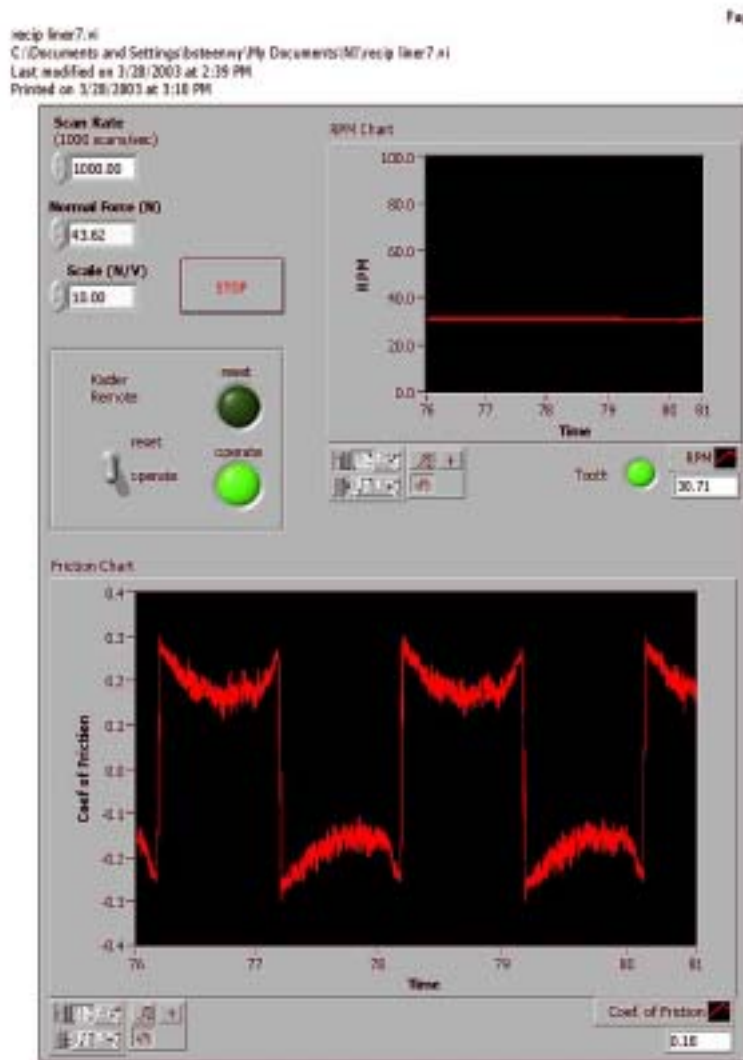
Experimental Study

(Piston Ring Reciprocating Cylinder Liner Test Rig - PRCLR)



Sample PRCL Friction Results

(Experimental Study)



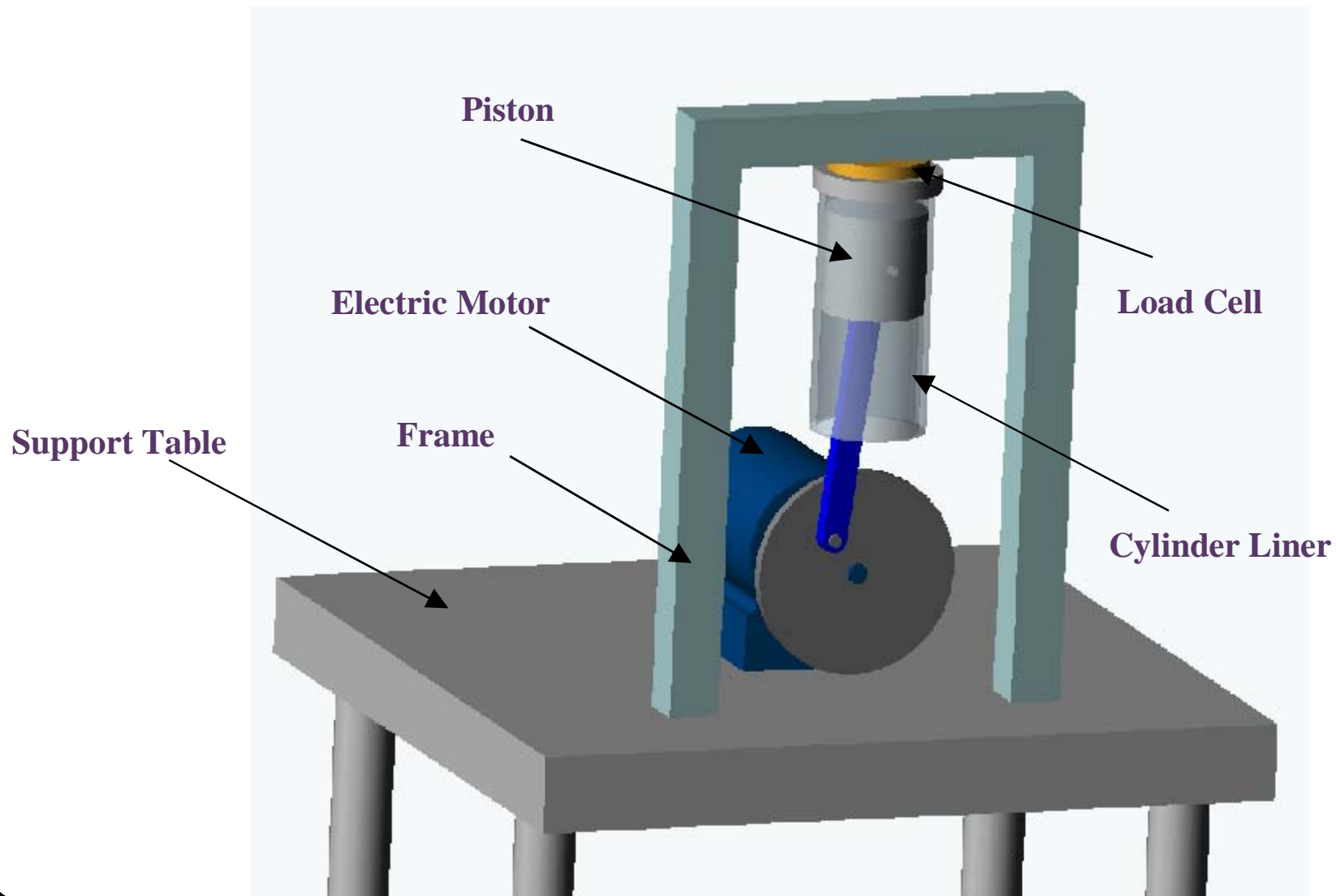
Coefficient of friction vs. Time

Future Experimental Studies

- Design & develop a crank slider (full piston & cylinder) operating under ambient conditions to measure
 - Friction
 - Film thickness (using interferometry technique)at the contact of OEM and laser machined PRCL interface
- Design & develop a single cylinder engine test rig operating in the presence of natural gas to measure friction at the contact of OEM and laser machined PRCL interface

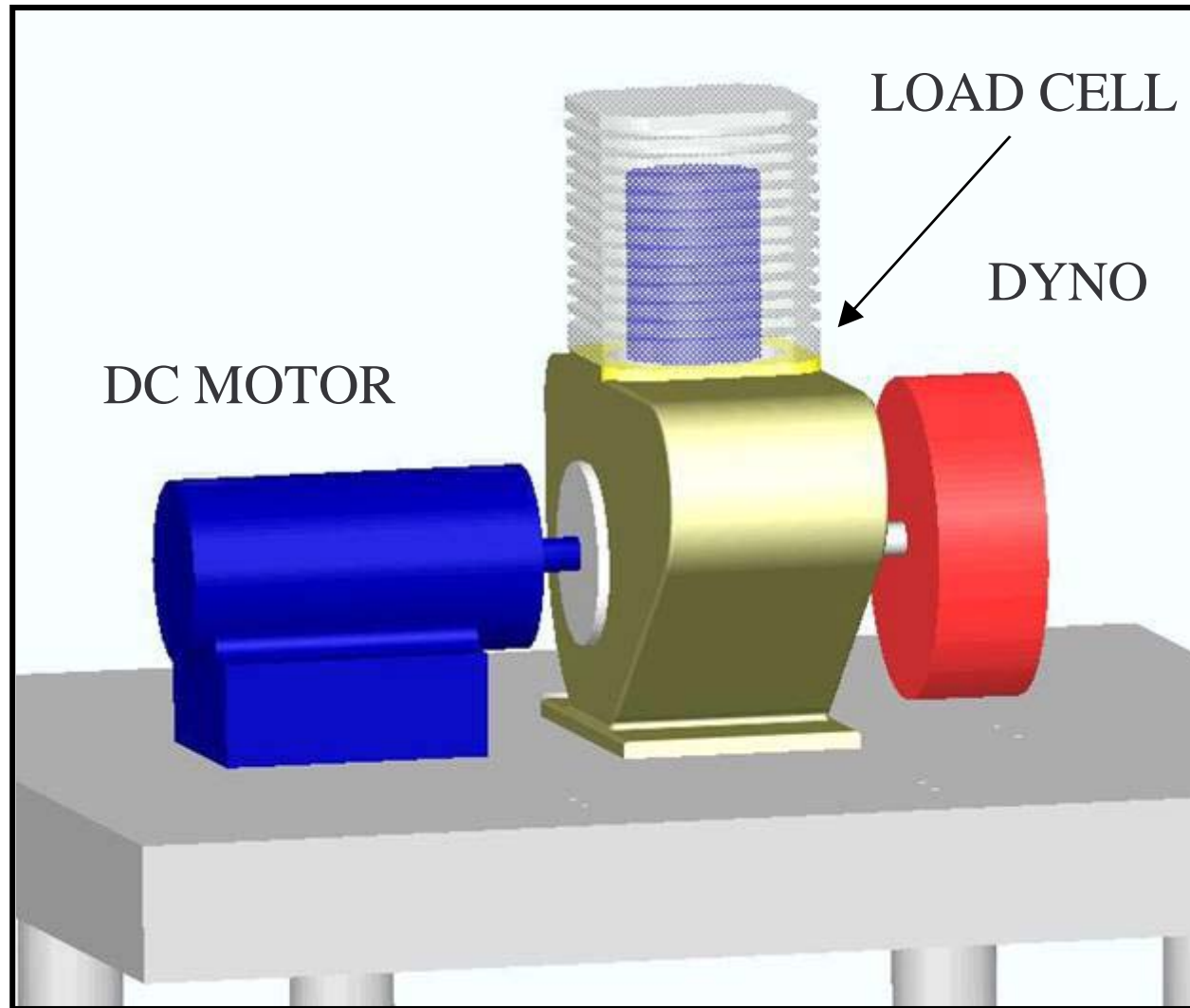
Future Full Size Piston Cylinder Machine

(To be Constructed)



Future Single or two Cylinder Engine Test Rig

(To be Constructed)

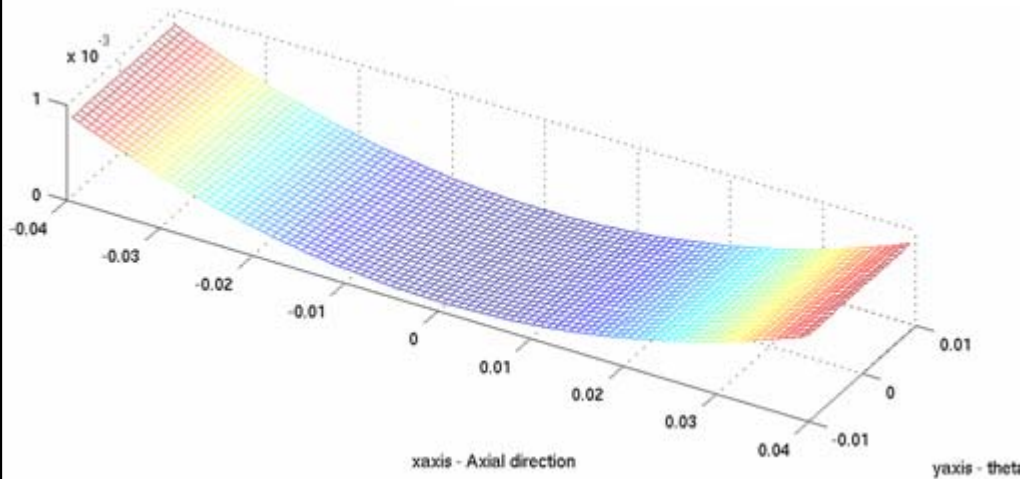
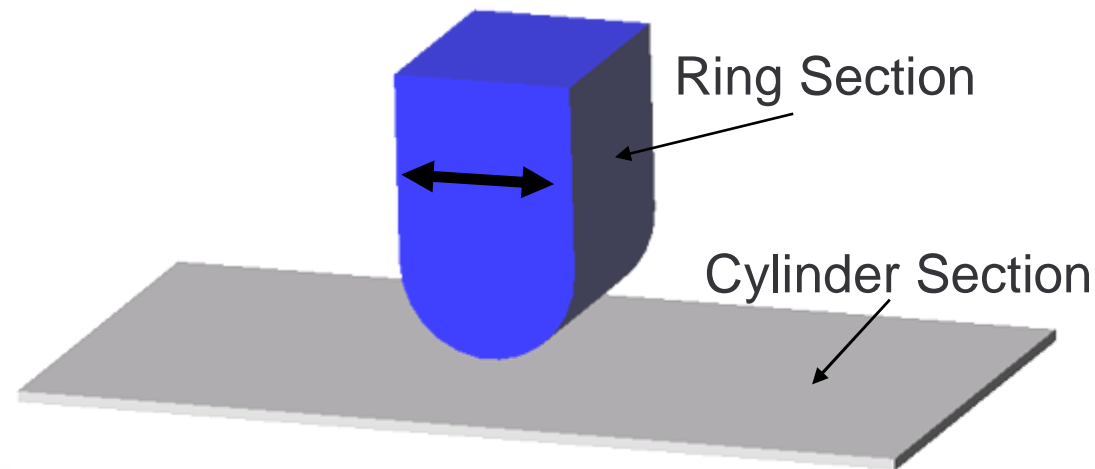


Analytical Investigation

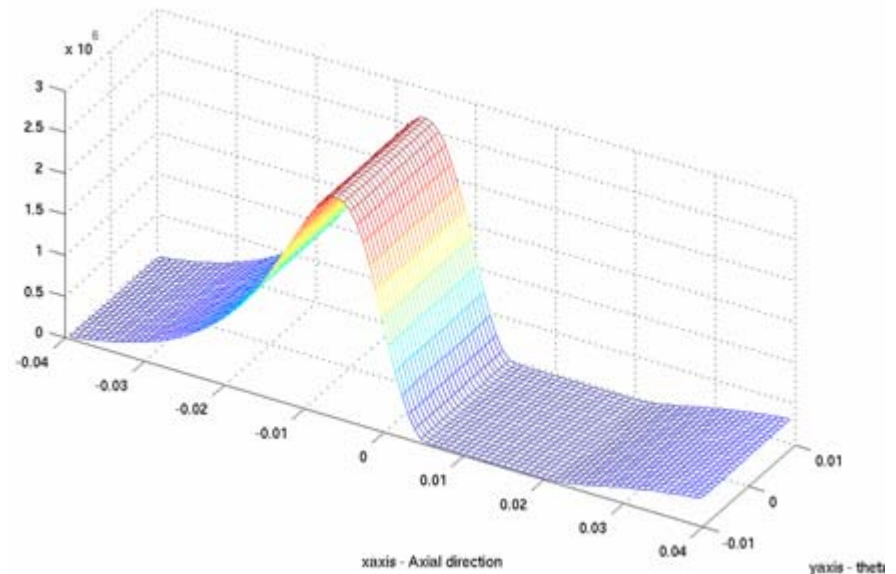
Analytical Study Accomplishments

- Hydrodynamic Lubrication of PRCL
- Elastohydrodynamic Lubrication of PRCL
- Kinematics, dynamics and secondary motion of the crank slider mechanism play a major role in the performance of the piston ring and cylinder liner interface

Ring Hydrodynamic Analysis



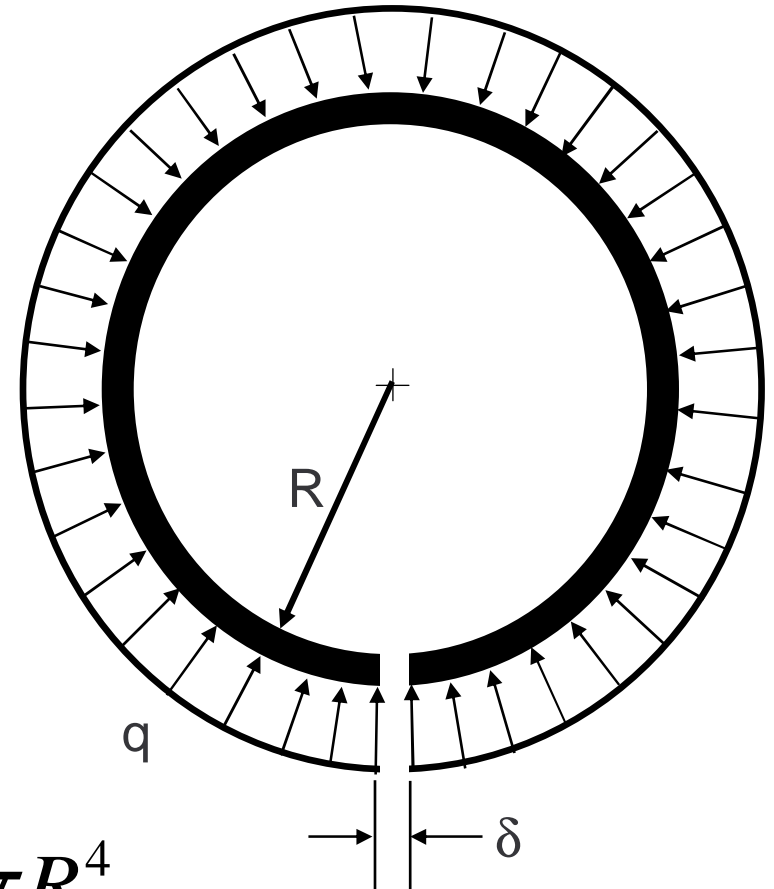
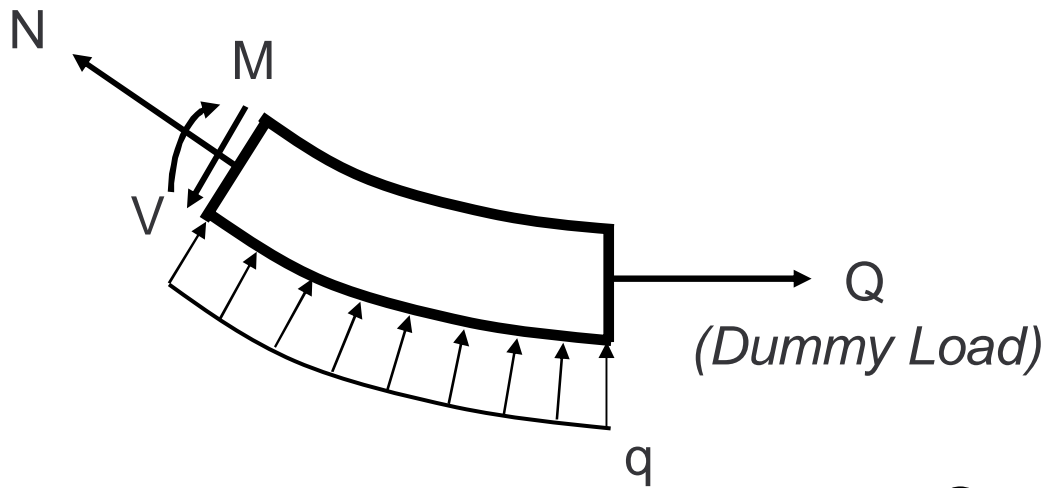
Film Thickness



Pressure Profile (expansion stroke)

Piston Ring Deflection

- Piston ring deflects as a function of pressure acting on its perimeter.



$$\delta = \frac{3\pi R^4}{EI} q$$

Crank-Slider Analysis

- In order to gain a complete understanding of the behavior of piston ring cylinder liner interface, a kinematic and dynamic analysis of the crank-slider mechanism is necessary.
- The kinematics analysis describes the motion of every link in the mechanism as a function of the input velocity and acceleration.
- With knowledge of the velocity and acceleration of the center of gravity of each link, the forces at every link and joint can be determined.

Kinematics

Vector Loop Approach : $\vec{R}_2 + \vec{R}_3 - \vec{R}_4 - \vec{R}_1 = 0$

Position

$$R_2 \cos \theta + R_3 \cos \theta - R_4 \cos \theta - R_1 \cos \theta = 0$$

$$R_2 \sin \theta + R_3 \sin \theta - R_4 \sin \theta - R_1 \sin \theta = 0$$

Velocity

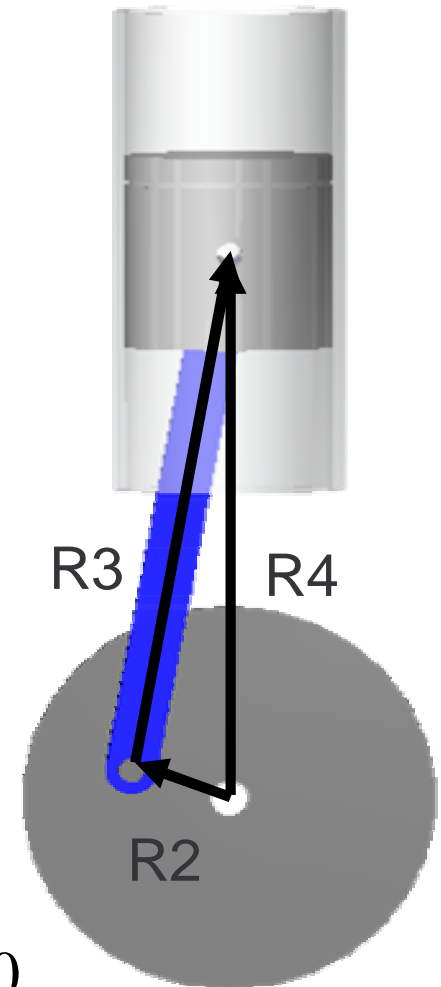
$$-R_2 \dot{\theta}_2 \sin \theta_2 - R_3 \dot{\theta}_3 \sin \theta_3 - \dot{R}_4 = 0$$

$$R_2 \dot{\theta}_2 \cos \theta_2 + R_3 \dot{\theta}_3 \cos \theta_3 = 0$$

Acceleration

$$-R_2 \ddot{\theta}_2 \sin \theta_2 - R_2 \dot{\theta}_2^2 \cos \theta_2 - R_3 \ddot{\theta}_3 \sin \theta_3 - R_3 \dot{\theta}_3^2 \cos \theta_3 - \ddot{R}_4 = 0$$

$$R_2 \ddot{\theta}_2 \cos \theta_2 - R_2 \dot{\theta}_2^2 \sin \theta_2 + R_3 \ddot{\theta}_3 \cos \theta_3 - R_3 \dot{\theta}_3^2 \sin \theta_3 = 0$$



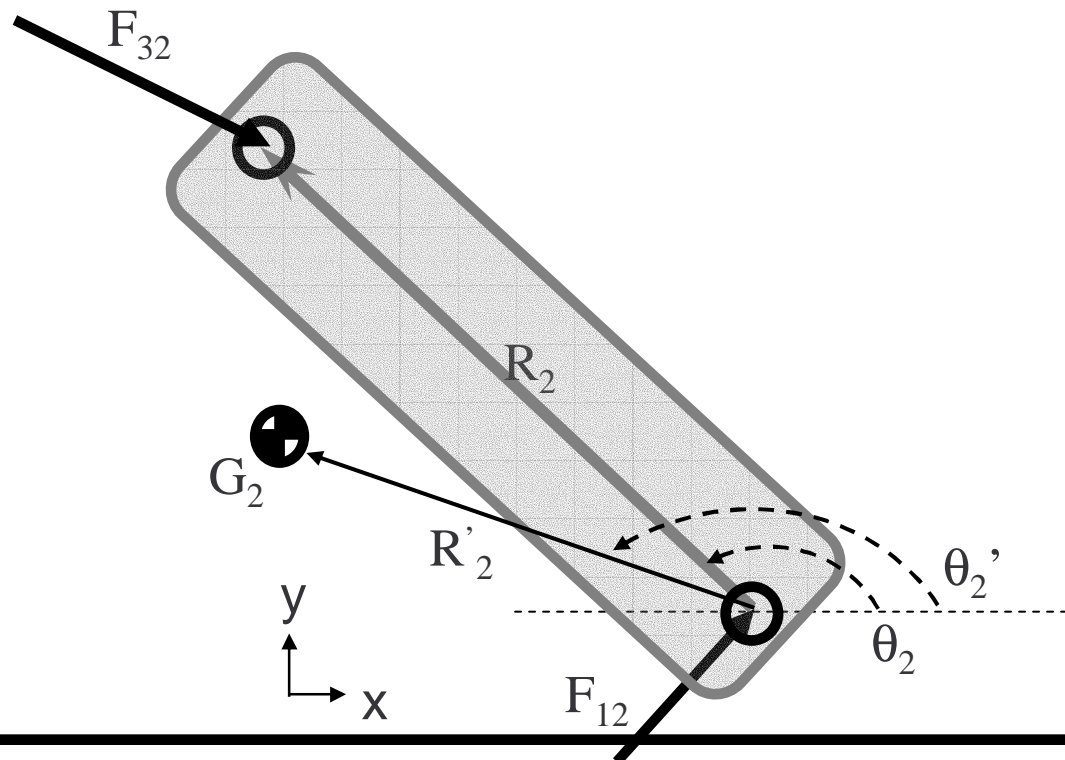
Dynamic Analysis

(FBD – Crank)

$$F_{12x} + F_{32x} = m_2 A_{g2x}$$

$$F_{12y} + F_{32y} = m_2 A_{g2y}$$

$$Q - (R_2 \sin \theta_2) F_{32x} + (R_2 \cos \theta_2) F_{32y} = -(R'_2 \sin \theta'_2) m_2 A_{g2x} + (R'_2 \cos \theta'_2) m_2 A_{g2y} + I_2 \alpha_2$$



Dynamic Analysis

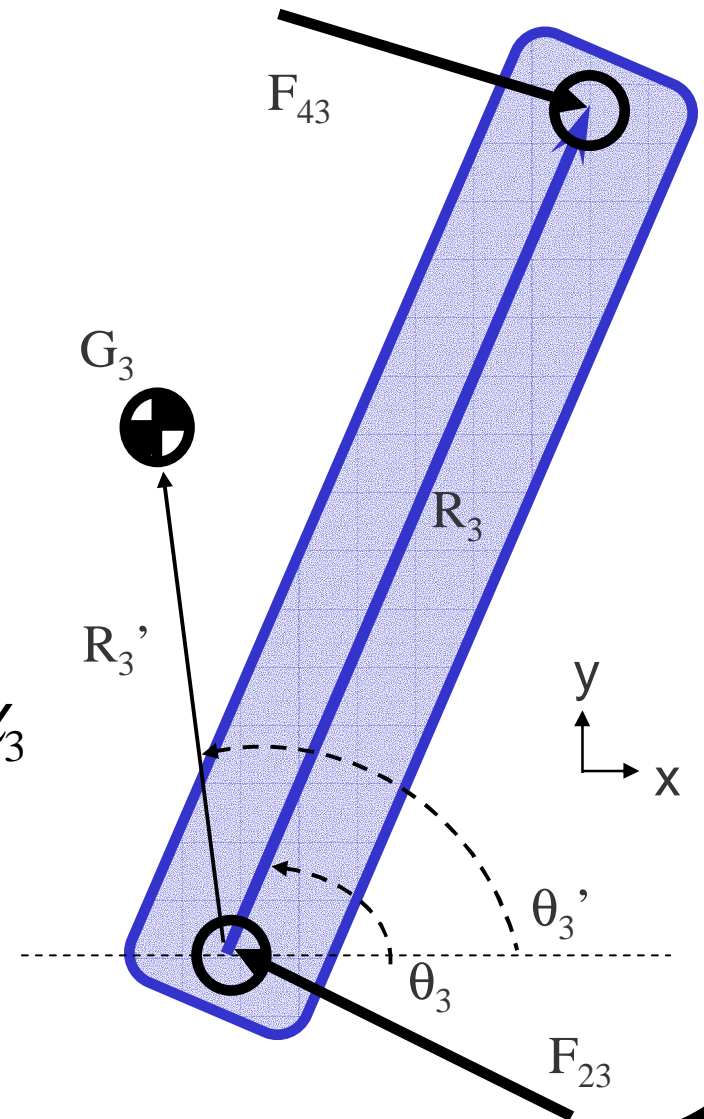
(FBD – Connecting Rod)

$$-F_{32x} + F_{43x} = m_3 A_{g3x}$$

$$-F_{32y} + F_{43y} = m_3 A_{g3y}$$

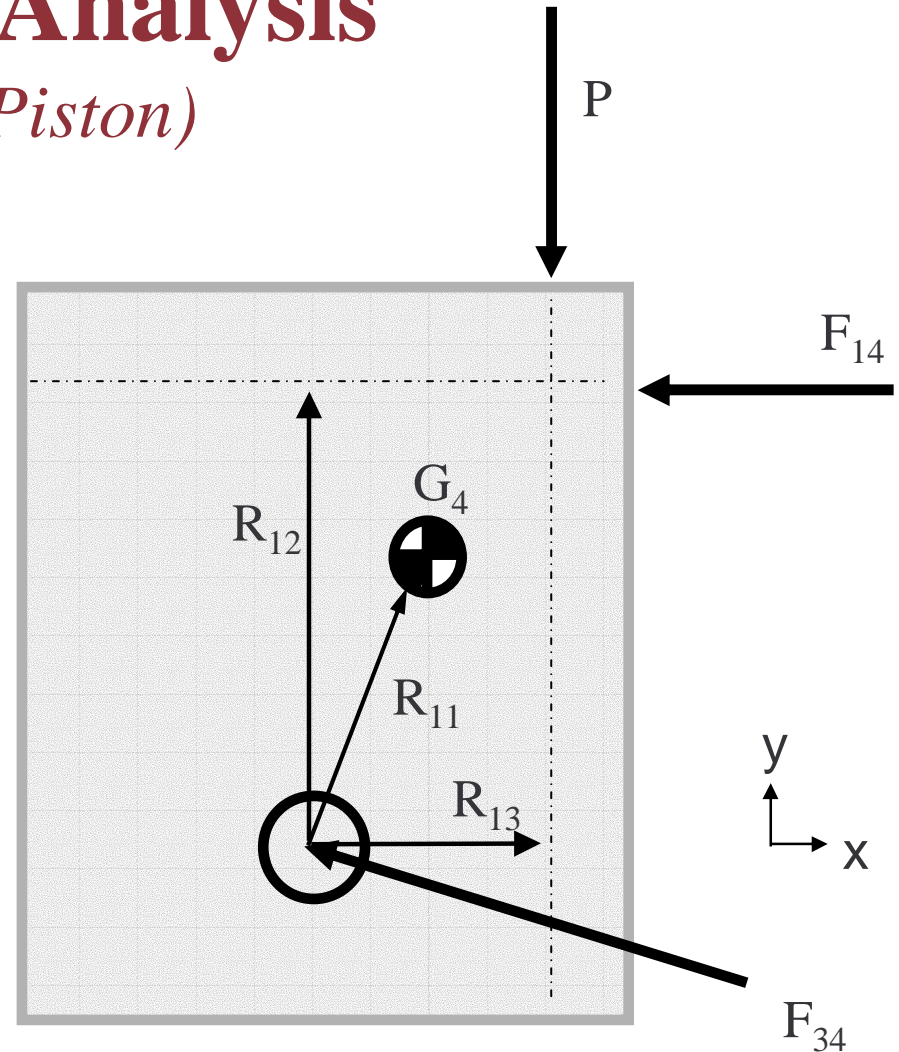
$$-(R_3 \sin \theta_3) F_{43x} + (R_3 \cos \theta_3) F_{43y} =$$

$$-(R'_3 \sin \theta'_3) m_3 A_{g3x} + (R'_3 \cos \theta'_3) m_3 A_{g3y} + I_3 \alpha_3$$



Dynamic Analysis

(FBD – Piston)



$$-F_{43x} + F_{14x} = m_4 A_{g4x} - P_x$$

$$-F_{43y} + F_{14y} = m_4 A_{g4y} - P_y$$

$$R_{12} F_{14x} = -(R_{11} \sin \theta_4) m_4 A_{g4x} + (R_{11} \cos \theta_4) m_4 A_{g4y} + R_{13} P$$

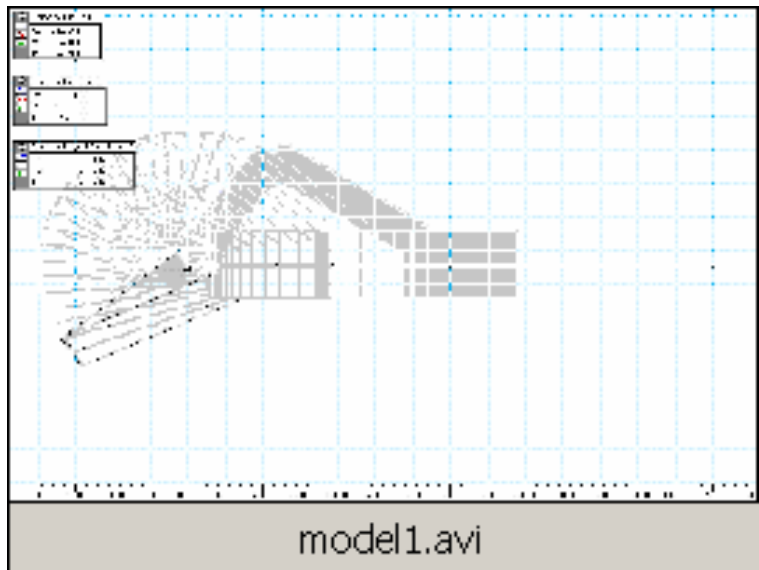
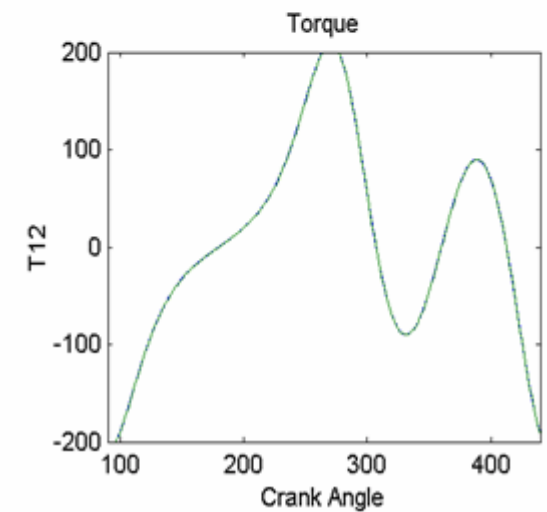
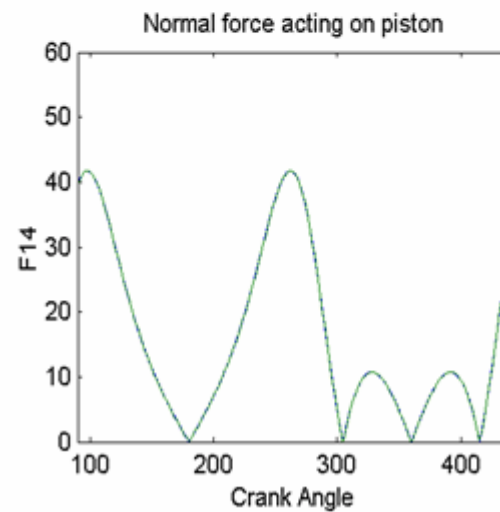
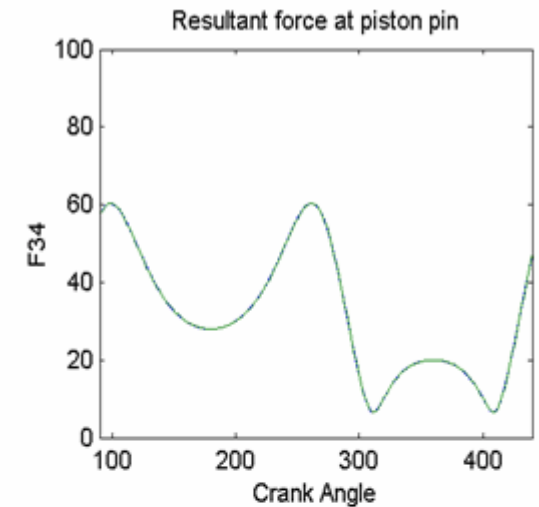
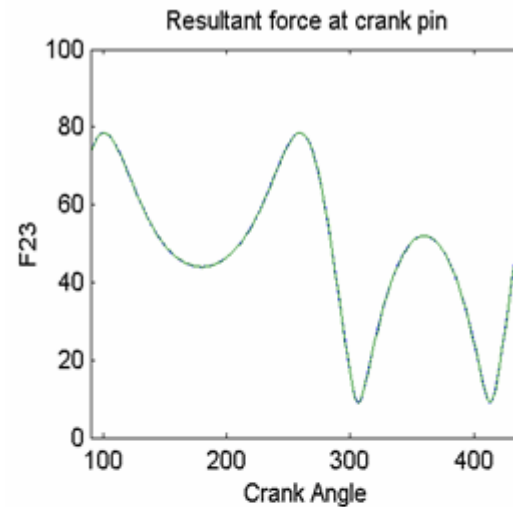
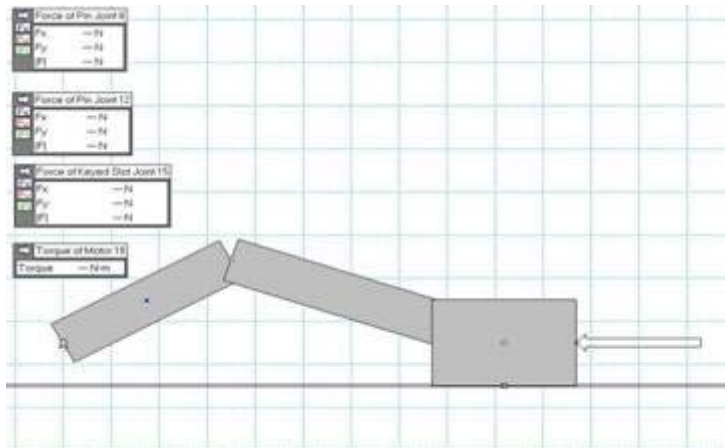
Dynamic Analysis

$$\begin{bmatrix}
 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & -R_2 \sin \theta_2 & R_2 \cos \theta_2 & 0 & 0 & 0 & 1 & 0 \\
 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & -R_3 \sin \theta_3 & R_3 \cos \theta_3 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & -1 & 0 & 1 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
 \end{bmatrix}
 \begin{bmatrix}
 F_{12x} \\
 F_{12y} \\
 F_{32x} \\
 F_{32y} \\
 F_{43x} \\
 F_{43y} \\
 F_{14} \\
 Q \\
 R_5 F_{14}
 \end{bmatrix}
 =
 \begin{bmatrix}
 m_2 A_{g2x} \\
 m_2 A_{g2y} \\
 I_2 \alpha_2 - (R'_2 \sin \theta'_2) m_2 A_{g2x} + (R'_2 \cos \theta'_2) m_2 A_{g2y} \\
 m_3 A_{g3x} \\
 m_3 A_{g3y} \\
 I_3 \alpha_3 - (R'_3 \sin \theta'_3) m_3 A_{g3x} + (R'_3 \cos \theta'_3) m_3 A_{g3y} \\
 m_4 A_{g4x} - Px \\
 m_4 A_{g4y} - Py \\
 -(R_4 \sin \theta_4) m_4 A_{g4x} + (R_4 \cos \theta_4) m_4 A_{g4y} - R_6 P
 \end{bmatrix}$$

- 9 X 9 set of linear equations
- Solve using Gaussian Elimination

Dynamic Analysis

(Validation using Working Model 2D)

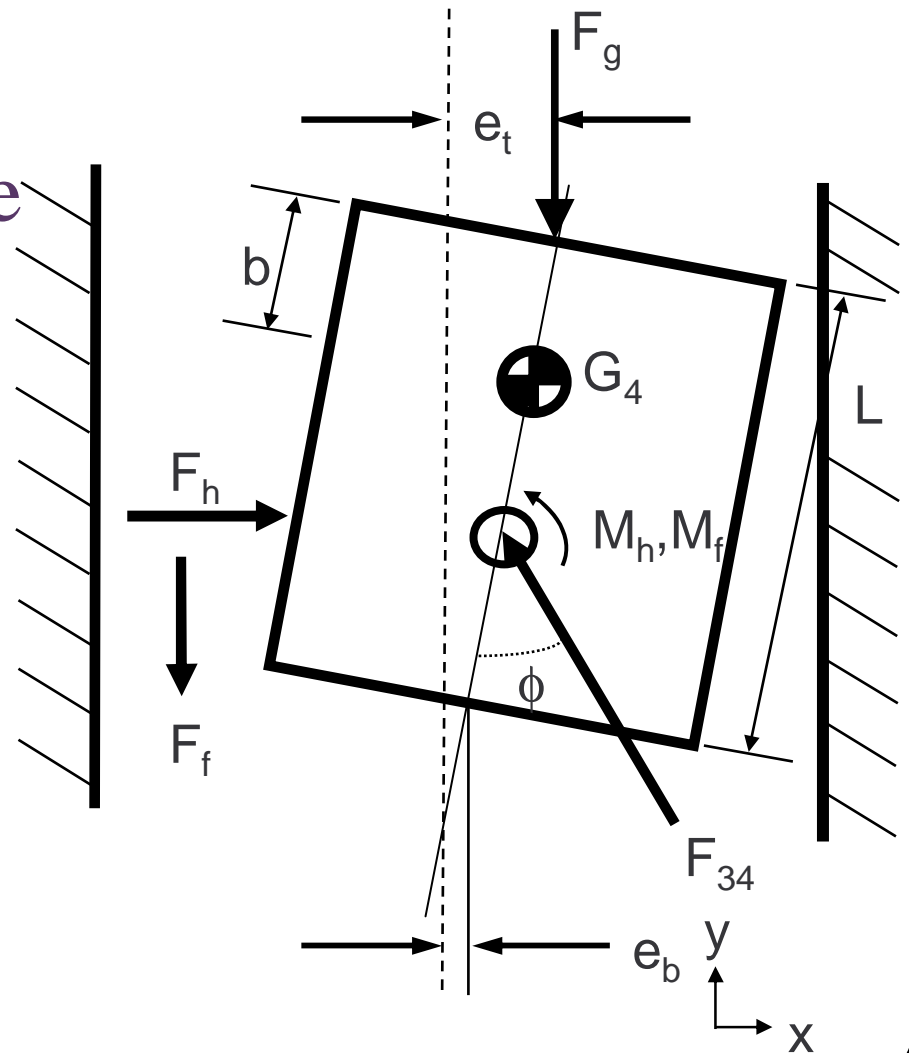


Secondary Motion of the Piston

- In the kinematic analysis, the piston motion was considered to be parallel to the axis of the cylinder.
- However, the piston can tilt and/or be offset relative to the centerline of the cylinder.
- The secondary motion of the piston provides the means through which the contact may react to the side load imposed by the dynamics of the slider-crank mechanism.

Secondary Motion

- Piston can be inclined and/or offset relative to the center line of the cylinder e_t & e_b .
- Forces acting on the piston
 - Cylinder gas pressure (F_g)
 - Frictional drag (F_f)
 - Hydrodynamic Force (F_h)
 - Dynamic Force (F_{34})



Secondary Motion

$$m_p \left[\ddot{e}_t \left(1 - \frac{b}{L} \right) + \ddot{e}_b \left(\frac{b}{L} \right) \right] = - \left(m_p A_{py} + F_g + F_f \right) \tan \phi + F_h$$

$$\frac{I_p (\ddot{e}_b - \ddot{e}_t)}{L} - m_p \left[\ddot{e}_t \left(1 - \frac{b}{L} \right) + \ddot{e}_b \left(\frac{b}{L} \right) \right] (a - b) = M_h + M_f$$

Secondary Motion

(Continued)

- A pair of nonlinear equations in e_t , e_b
- Solve using Newton method

$$F_h = \int_0^L \int_0^{2\pi} P(\theta, y) R \cos \theta d\theta dy$$

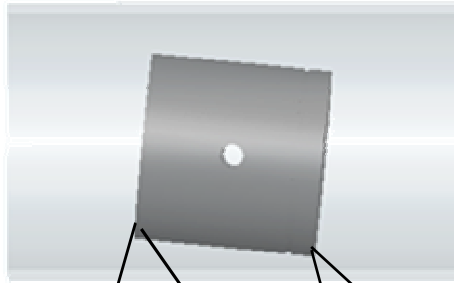
$$M_h = \int_0^L \int_0^{2\pi} [P(\theta, y) R \cos \theta] (y - y_{pin}) d\theta dy$$

$$F_f = \int_0^L \int_0^{2\pi} \left(\frac{h}{2} \frac{\partial P}{\partial y} + \mu \frac{\dot{R}_4}{h} \right) R d\theta dy$$

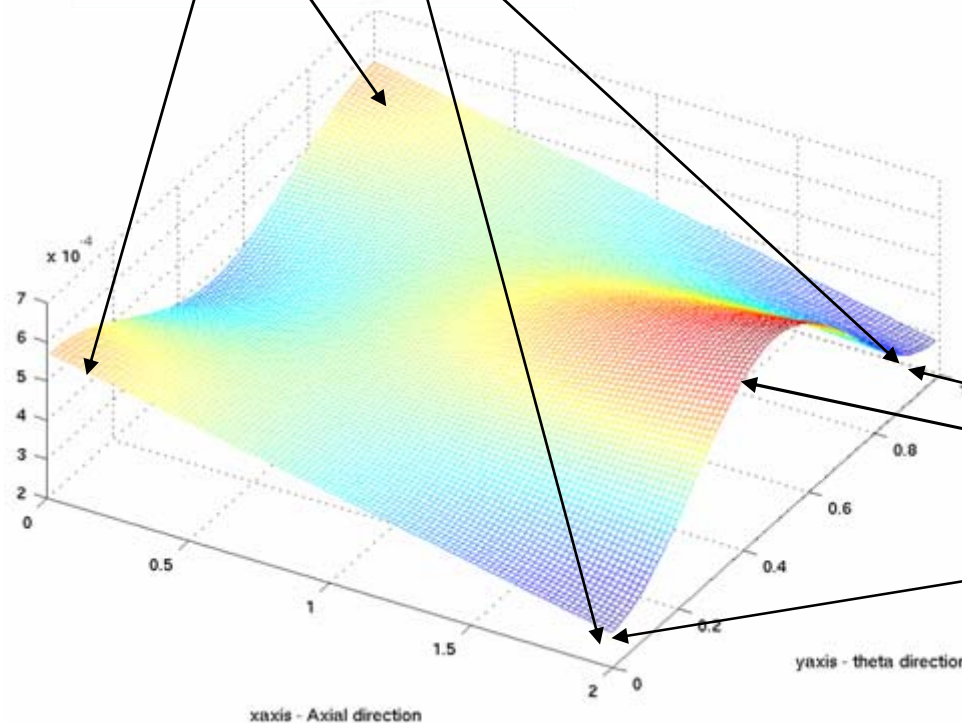
$$M_f = \int_0^L \int_0^{2\pi} \left(\frac{h}{2} \frac{\partial P}{\partial y} + \mu \frac{\dot{R}_4}{h} \right) R \cos \theta d\theta dy$$

Piston/Cylinder Typical Film Thickness

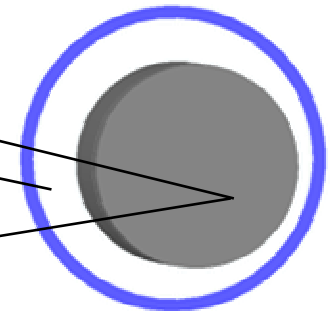
Side View



$$h = \left\{ c - \left[e_b - (e_b - e_t) \frac{x}{L} \right] \cos \theta \right\}$$



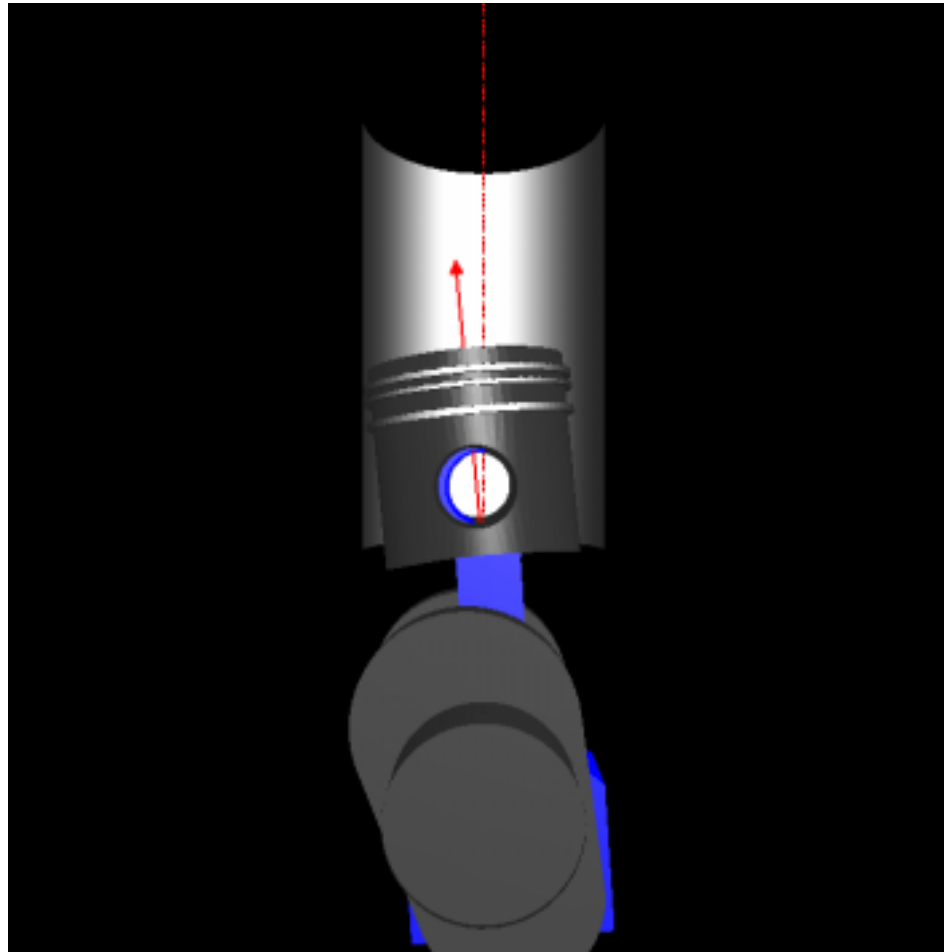
Top View



Unwrapped Piston Film Thickness ([Movie](#))

Piston/Cylinder Secondary Motion

- Note the Tilt of the piston



Future Analytical Work

- Investigate the effects of surface patterning on lubrication of the PRCL interface
- Correlate the experimental and analytical results from the PRCL rig
- Investigate the effects of piston secondary motion on lubrication of piston ring cylinder liner interface
- Include the effects of the hydrodynamic lubrication of the con-rod and wrist-pin bearings on the motion and dynamics of the piston secondary motion.

Summary

- A PRCL rig has been designed and developed
- PRCL rig will undergo testing & evaluation
- Preliminary design of future test rigs have been completed.
- A model for hydrodynamic lubrication of PRCL interface has been developed and validated.
- A Model for piston dynamics and secondary motion has been developed to better understand the complicated (tilt) motion of the piston in the liner

Summary

(Continued)

- The analytical model will be used to investigate the effects of surface patterning on lubrication of piston ring cylinder liner interface.
- Analytical experimental results will be corroborated.

Acknowledgments

- The author would like to thank DOE – NETL for their support of this research study.